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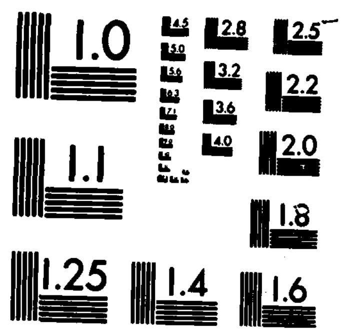

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SPACE-VARIANT OPTICAL SYSTEMS

Final Technical Report

on

AFOSR Grant 79-0076

(Sept. 30, 1979 - Sept. 30, 1984)

by

John F. Walkup and Thomas F. Krile
Co-Principal Investigators

November 1984

Optical Systems Laboratory

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Both experimental and analytical investigations of 1-D and 2-D, coherent and incoherent space-variant optical processors have been conducted. The investigations included 1) continuation of previous work on multiplexed holograms with phase-coded reference beams, 2) construction of a computer-controlled laser plotter, 3) design of incoherent processors which use color as an extra parameter, 4) applications of acousto-optical modulators and time-integrating detectors to space-variant processors, 5) initiation of piecewise-isoplanatic model investigations, and 6) initiation of studies on the use of space-variant systems for binary numerical optical computing. cont Keywords include

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ABSTRACT

Both experimental and analytical investigations of 1-D and 2-D, coherent and incoherent space-variant optical processors have been conducted. The investigations included 1) continuation of previous work on multiplexed holograms with phase-coded reference beams, 2) construction of a computer-controlled laser plotter, 3) design of incoherent processors which use color as an extra parameter, 4) applications of acousto-optical modulators and time integrating detectors to space-variant processors, 5) initiation of some piecewise-isoplanatic model investigations, and 6) initiation of studies on the use of space-variant systems for binary numerical optical computing.

RESEARCH OBJECTIVES

The major research objectives during the period of the grant, from September 30, 1979 to September 30, 1984, have been to analytically and experimentally investigate the optical implementation of space-variant information processing operations. Both one-dimensional (1-D) and two-dimensional (2-D) signal processors using both coherent and incoherent illumination have been studied. The major areas of investigation have been (1) the continuation of work begun under the previous grant (AFOSR 75-2855) to represent 2-D space-variant systems using multiplexed holography with phase-coded reference beams, (2) the construction of a computer-controlled laser scanner/plotter facility; (3) the design of 2-D space variant processors using incoherent illumination with color as an extra variable; (4) the application of acousto-optical (AO) modulators with time-integrating detectors for 1-D and 2-D space variant operations, (5) the initiation of a comprehensive study of the piecewise-isoplanatic approximation (PIA) for reducing the resolution requirements of sampled 2-D space-variant processors; and (6) the development of architectures for numerical optical space-variant processing, binary multiplication in particular. Details are provided in the following sections.

SUMMARY OF RESULTS

Due to the large number of journal publications and scientific reports from this research, plus the fact that the program of research is continuing under AFOSR Grant 84-0382, we will briefly summarize the major results obtained in this section, with references made to the appropriate publications and reports.

(1) Multiplexed Holography with Phase-Coded Reference Beams.

Much of our work on our previous grant was based on spatially sampling the input plane of a 2-D space-variant system and using phase-coded reference beams to multiplex the resulting transfer function holograms.[1-4] Several extensions of this work were performed under this grant. First, a particular family of codes called Gold codes was extensively investigated, both experimentally and via computer simulations, for use as reference beam phase codes.[5] They are attractive for multiplexed holography systems in that a given family has many different member codes (a different code is needed for each input sample point), and there are known bounds on the cross-correlations of each pair of member codes. However, except for systems which have delta-like impulse responses, a large number of bits are needed to reduce crosstalk noise, so typical 64 x 64 code arrays don't perform very well.

As part of the Gold-code study, a facility for construction and testing of binary phase diffuser masks on photoresist was set up.[6,7] The fabrication was done using the UV line of an argon-ion laser in conjunction with a computer-controlled laser scanner to write the phase masks directly on a photoresist plates. A number of microscopic and macroscopic testing procedures were developed to evaluate the quality of the resulting masks. Good masks were then used as reference-beam encoders in two multiplexed holography space-variant systems.

The area of computer-generated multiplexed holography was also advanced from the previous grant.[8-10] This technique has a number of advantages over photographically-constructed multiplex holograms in that there is no bias buildup problem, unwanted terms due to the nonlinear recording of a conventional hologram can be eliminated, and the resulting computer generated hologram has a larger dynamic range.

Finally, a sampled input/sampled transfer function approach to multiplexing was developed which completely eliminates cross talk noise without the need for coded reference beams.[11-13] It requires a replicated input function for playback, and several techniques for obtaining the replication were proposed.

(2) Computer Controlled Laser Scanner Facility

The ability to produce high quality computer-generated holograms (CGH's) was needed on this grant, so a computer-controlled laser plotter facility was constructed.[14,15] It consists of a micro-processor controlled shutter (AO modulator) and beam scanner (galvanometer-driven X-Y mirrors) along with associated beam-forming optics. The facility presently has the capability of writing a 1024 x 1024 pixel image directly on a 1.7 cm. square piece of film or photoresist with 256 gray levels per pixel. The recording medium determines the laser wavelength used as the illuminating source. The functions to be plotted can be computed off-line on a VAX 11/780 and down loaded to the mircroprocessor (a Compucolor or Apple III), or can be generated directly by the microprocessor. Curves which describe the behavior of the recording material can be stored in the microprocessor and used to compensate for nonlinearities. Both CGH's and binary phase masks on photoresist have been produced using this system.

(3) 2-D Space-Variant Processors Using Color

Progress in this area developed along three lines. First a rather exhaustive study of the use of independent color/polarization channels in additive, subractive, and hybrid additive/subtractive incoherent systems was made.[16] In order to implement a space-variant processor, one needs to be able to represent complex inputs and kernels, multiply them, and integrate (sum) the results. Since multiplying complex numbers involves multiplying their magnitudes and adding their phases, problems arise when using strictly either an additive (good for addition) or subtractive (good for multiplication) color system. Thus, a hybrid additive/subtractive system seems indicated, but even so a large number of channels and electronic post-procesing operations may be necessary.

After it was pointed out by a colleague, Dr. M.O. Hagler, that a color TV tristimulus system forms a 3-D linear vector space, a new incoherent space-variant processor was developed.[17-19] It uses color TV cameras and monitors to represent and operate on complex numbers in the 3-D space defined by the National Standards for Color TV transmissions (the NTSC standards). This space can be viewed as a 2-D plane represented by hue and saturation parameters and an orthogonal axis represented by illuminance. In this system, multiplication of numbers (input and kernel) represented in polar form is done by controlling hue and saturation separately from intensity. The phase angles of the numbers to be multiplied are displayed as the saturations of two complementary hues for positive and negative phase angles and are then combined in an additive system. The intensities are manipulated separately in a subtractive system (back-to-back neutral density filters) to represent the multiplication of two complex number magnitudes. The results of the multiplication are detected by a color TV camera (phase angle) and a black-and-white camera (amplitude). A polar-to-rectangular transformation is then done electronically on the output signals from the cameras. The transformed output is fed to the chrominance (hue and saturation) inputs of a color TV monitor, keeping the intensity constant. The output of this monitor, now in complex rectangular form, is then summed by a collecting lens and the result is detected by another color TV camera. Thus, since both the operations of complex multiplication and addition can be done, the space-variant superposition integral can be evaluated. All components of this system were tested and reported in the literature.[19] Further development awaits color cameras and monitors with greater linearity and less noise than those presently available.

In a third approach to performing a 2-D space-variant operation, it was noted that the 2-D kernel $h(x,y;\xi,\eta)$ is a 4-D function, and one difficulty is in making enough physical parameters available to represent it. Our solution was to assume that $h(\cdot)$ is separable in Cartesian coordinates, (i.e. $h(x,y;\xi,\eta) = h_1(x,\xi)h_2(y,\eta)$ and to use a white light coherent processor so that wavelength provides us with an additional parameter.[20-22] The processor makes use of the dispersive properties of prisms, as well as an achromatic Fourier transformer, as part of its operation. It has a form similar to two tandem 1-D processors but performs a 2-D operation. A significant advantage of having a separable kernel h(·) is that the space-bandwidth product of the input can be equal to the space-bandwidth product of the system, rather than being limited to the square root of the latter.

(4) AO Modulators in Time-Integrating Space-Variant Systems

There were two projects initiated under this grant in this area. In the first project, time is being used as the extra physical parameter in forming the 4-D kernel h(·) for a 2-D space-variant processor. A raster scan of the input with point sampling is used along with a time-integrating detector in the output plane of the processor.[23-25] The unique feature of this system is that the 2-D kernel which operates on each input point is formed by using two orthogonally-positioned ("crossed") AO modulators. By varying the frequency and amplitude of the time signals to the drivers of the x-and y-axis modulators one can direct the output to appear at a predetermined point (or points) in the output plane with an arbitrarily scaled amplitude. The 2-D kernels operating on each pixel must be separable in x and y for this system, but each pixel can have a kernel different from every other pixel, so it should be possible to implement a large class of space-variant operations. A proof-of-principle experiment was performed and reported on to verify the concept,[23-25] and further development awaits the arrival of faster AO modulator drivers.

A second project in this area was the development of a 1-D real-time space-variant processor. The idea was proposed by Dr. Hagler, and involves the merging of two projects completed under the previous grant, namely 1-D generalized space-variant processor implementations and a scanning technique to implement 2-D space-variant operations without the need for a 2-D input modulator.[26] The input to the processor can be obtained from a time-modulated scanned laser beam or from a "snapshot" of an input AO modulator. The processor itself is of the standard form which we have developed previously, namely a 2-D mask, representing the 2-D space-variant kernel, followed by an astigmatic lens system. The system output, along with an on-axis reference beam, is recorded on a time-integrating CCD array. Thus we are essentially recording a multiplexed hologram which preserves the amplitude and phase of the desired output signal. However, since we don't use an optical readout of the "hologram", it turns out that the detector array doesn't need the high resolution required to record holographic fringes, but only enough resolution to record the output signal itself. The desired output signal is obtained by taking the voltage signal from the CCD array and passing it through a DC blocking capacitor to remove the "hologram's" bias term. This project is in the initial stages of the experimental verification and is being continued under the present grant.

(5) Piecewise-Isoplanatic Space-Variant Systems

All of the 2-D space-variant processors developed thus far have been sampled systems, and thus resolution and time-bandwidth product limitations restrict the inputs to low-resolution functions or images. If the space-variant system can be modelled as piecewise-isoplanatic (as in imaging in a turbulent medium), then a relatively few input samples can be used with an equal number of space-variant kernels to characterize the system. An investigation of this neglected but potentially important area of piecewise-isoplanatic approximations has recently been initiated. Important progress has already been made in developing improved measures of a generalized linear system's isoplanaticity using both spatial and spatial frequency parameters. Using these measures, one can determine <u>apriori</u> whether or not a given linear system's output will converge properly when modelled with the piecewise isoplanatic approximations. Further investigations in this area are continuing under the present grant.

(6) Numerical Optical Space-Variant Computing

The main goal of this project is to apply optical space-variant processing techniques to the area of discrete numerical computations, primarily binary arithmetic. The particular problem of implementing binary multiplication was chosen because it contains the major operations required of a computer's arithmetic logic unit. The approach we developed represents a compromise among several of the problems inherent in residue arithmetic and convolutional techniques for multiplication.[27-29] In order to speed up the operation, the binary multiplier is broken up into groups of bits and the decimal value of each group is encoded using wavelength as a parameter. For an n-bit group we have 2^n different values represented by 2^{n-1} different colors plus no light. A prism or grating is then used to perform a color-to-spatial position transformation directing the color-coded multiplier data to appropriate locations on a liquid crystal light valve (LCLV). There the data from the multiplier groups are matched up with replicated and shifted multiplicand bits which are imaged onto the LCLV. The thresholding function (AND operation) of the LCLV is then used to form all partial products simultaneously. On the output side of the LCLV a lens is used to form the sums of partial products in mixed binary form. If 2-bit multiplier groups are used, there are only four levels possible for each bit position of the partial products, instead of the n levels for a convolutional-type multiplier using n-bit numbers. Thus the accuracy we obtain in converting back to the pure binary format will be greater than in the convolutional case. To produce the desired output from the mixed binary data a feedback system using the threshold properties of the LCLV is used which automatically takes care of propagating carries. The two major subsystems of this binary multiplier were experimentally verified except for the feedback operation. This work is continuing with a view to speeding up the partial product formation and increasing the accuracy and throughput of the mixed binary-to-binary converter.

In summary, much progress has been made in the implementation of both coherent and incoherent space-variant optical signal processors, and new ground has been broken in the areas of piecewise isoplanantic systems and optical binary arithmetic processors.

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3. S. H. Lin, T. F. Krile, J. F. Walkup, "PIA Modeling of Linear Space-Variant Systems" (to be submitted to J. Opt. Soc. Am-A, 1985).

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SUMMARY OF SIGNIFICANT ACCOMPLISHMENTS

1. Development of a sampled input/sampled transfer function approach to 2-D space-variant processor implementation.

2. Construction of a computer-controlled laser scanner/plotter facility for direct fabrication of computer generated holograms and binary phase masks.

3. Experimental investigation of techniques for the fabrication and testing of binary phase masks on photoresist.

4. Analysis and design of a coherent 2-D space-variant processor using computer generated multiplexed holograms with random amplitude and Gold-coded phase diffuser masks.

5. Extensive investigations of the use of multiple color and polarization channels for incoherently implementing space-variant operations in additive, subtractive, and "hybrid" additive/subtractive optical systems.

6. Development of an incoherent hybrid optical/electronic space-variant processor based on the tristimulus space of color television.

7. Development of a technique using color-encoded, tandem 1-D white light optical processors to perform 2-D space variant processing.

8. Investigation of a technique for performing a 2-D space variant operation using a time-integrating detector and two crossed AO modulators to form the system impulse response.

9. Investigation of an optical processor to filter temporal signals which employs a 1-D space-variant system and a real-time holographic recording technique using a CCD detector array.

10. Initiation of a project on the use of space-variant techniques in performing binary numerical optical processing operations which resulted in the design of a binary optical multiplier using color encoding.

11. Initiation of a comprehensive study of the piecewise isoplanatic approximation as a model for space-variant systems resulting in a new measure for linear system isoplanaticity.

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